Cleaning up crypto
Tanja Lange, T. U. Eindhoven
Joint work with:
Peter Schwabe, R. U. Nijmegen

http://xkcd.com/538/
AES-128, RSA-2048, etc. are widely accepted standards. Obviously infeasible to break by best attacks in literature. Implementations are available in public cryptographic libraries such as OpenSSL. Common security practice is to use those implementations.
AES-128, RSA-2048, etc. are widely accepted standards. Obviously infeasible to break by best attacks in literature. Implementations are available in public cryptographic libraries such as OpenSSL.

Common security practice is to use those implementations. But cryptography is still a disaster! Complete failures of confidentiality and integrity.
We have designed and implemented a new cryptographic library, NaCl (“salt”), to address the underlying problems.

nacl.cace-project.eu, nacl.crypt.to: source and extensive documentation.

Acknowledgments: code contributions from Matthew Dempsky (Mochi Media), Niels Duif (Eindhoven), Emilia Käsper (Leuven), Adam Langley (Google), Bo-Yin Yang (Academia Sinica).
Most of the Internet is cryptographically unprotected. Primary goal of NaCl: Fix this.

Main task: **public-key authenticated encryption**.

Alice has a message $m$ for Bob.

Uses Bob’s public key and Alice’s secret key to compute authenticated ciphertext $c$. Sends $c$ to Bob.

Bob uses Alice’s public key and Bob’s secret key to verify and recover $m$. 
Alice using a typical cryptographic library:

Generate random AES key.
Use AES key to encrypt packet.
Hash encrypted packet.
Read RSA key from wire format.
Use key to sign hash.
Read Bob’s key from wire format.
Use key to encrypt signature etc.
Convert to wire format.

Plus more code:
allocate storage,
handle errors, etc.
Alice using NaCl:

c = crypto_box(m, n, pk, sk)
Alice using NaCl:
\[ c = \text{crypto\_box}(m, n, pk, sk) \]

32-byte secret key \( sk \).
32-byte public key \( pk \).
24-byte nonce \( n \).
\( c \) is 16 bytes longer than \( m \).

All objects are C++\nstd::string variables represented in wire format, ready for storage/transmission.

C NaCl: similar, using pointers; no memory allocation, no failures.
Bob verifying, decrypting:
m=crypto_box_open(c,n,pk,sk)

Initial key generation:
pk = crypto_box_keypair(&sk)
Bob verifying, decrypting:
m = crypto_box_open(c, n, pk, sk)

Initial key generation:
pk = crypto_box_keypair(&sk)

Can instead use signatures for public messages:

pk = crypto_sign_keypair(&sk)

64-byte secret key, 32-byte public key.

sm = crypto_sign(m, sk)

64 bytes overhead.

m = crypto_sign_open(sm, pk)
“This sounds too simple! Don’t applications need more?”
“This sounds too simple! Don’t applications need more?”

Examples of applications using NaCl’s *crypto_box*:

DNSCurve and DNSCrypt, high-security authenticated encryption for DNS queries; deployed by OpenDNS.

QUIC, Google’s TLS replacement.

MinimaLT in Ethos OS, faster TLS replacement.

Threema, encrypted-chat app.
No secret load addresses


Almost all AES implementations use fast lookup tables. Kernel’s secret AES key influences table-load addresses, influencing CPU cache state, influencing measurable timings of the attack process. 65ms to compute influence\(^{-1}\).
Most cryptographic libraries still use secret load addresses but add “countermeasures” intended to obscure influence upon the CPU cache state. Not confidence-inspiring; likely to be breakable.
Most cryptographic libraries still use secret load addresses but add “countermeasures” intended to obscure influence upon the CPU cache state. Not confidence-inspiring; likely to be breakable.

NaCl systematically avoids all loads from addresses that depend on secret data. Eliminates this type of disaster.

2010 Langley ctgrind: verify this automatically.
No secret branch conditions

2011 Brumley–Tuveri: minutes to steal another machine’s OpenSSL ECDSA key. Secret branch conditions influence timings.

Most cryptographic software has many more small-scale variations in timing: e.g., memcmp for IPsec MACs.
No secret branch conditions

2011 Brumley–Tuveri: minutes to steal another machine’s OpenSSL ECDSA key. Secret branch conditions influence timings.

Most cryptographic software has many more small-scale variations in timing: e.g., memcmp for IPsec MACs.

NaCl systematically avoids all branch conditions that depend on secret data. Eliminates this type of disaster.
1998 Bleichenbacher: Decrypt SSL RSA ciphertext by observing server responses to $\approx 10^6$ variants of ciphertext.

SSL first inverts RSA, then checks for “PKCS padding” (which many forgeries have). Subsequent processing applies more serious integrity checks.

Server responses reveal pattern of PKCS forgeries; pattern reveals plaintext.
Typical defense strategy: try to hide differences between padding checks and subsequent integrity checks. But hard to get this right: see, e.g., Crypto 2012 Bardou–Focardi–Kawamoto–Steel–Tsay, 2013.02.04 Alfardan–Paterson.
Typical defense strategy: try to hide differences between padding checks and subsequent integrity checks. But hard to get this right: see, e.g., Crypto 2012 Bardou–Focardi–Kawamoto–Steel–Tsay, 2013.02.04 Alfardan–Paterson. NaCl does not decrypt unless message is authenticated. Verification procedure rejects all forgeries in constant time. Attacks are further constrained by per-nonce key separation and standard nonce handling.
Centralizing randomness

2008 Bello: Debian/Ubuntu OpenSSL keys for 1.5 years had only 15 bits of entropy.

Debian developer had removed a subtle line of OpenSSL randomness-generating code.
Centralizing randomness

2008 Bello: Debian/Ubuntu OpenSSL keys for 1.5 years had only 15 bits of entropy.

Debian developer had removed a subtle line of OpenSSL randomness-generating code.

NaCl uses /dev/urandom, the OS random-number generator. Reviewing this kernel code is much more tractable than reviewing separate RNG code in every security library.
Centralization allows OS to merge many entropy sources into pool feeding many applications.

Merging is deterministic and auditable. Can survive many bad/failing/malicious sources if there is one good source.
Centralization allows OS to merge many entropy sources into pool feeding many applications. Merging is deterministic and auditable. Can survive many bad/failing/malicious sources if there is one good source.

Huge step backwards: Intel’s RDRAND in applications. Single entropy source; no backup; likely to be poorly cloned; backdoorable (CHES 2013); non-auditable. Not used in NaCl.
Avoiding unnecessary randomness

2010 Bushing–Marcan–Segher–Sven: Sony ignored ECDSA requirement of new randomness for each signature. \( \Rightarrow \) Signatures leaked PS3 code-signing key.
Avoiding unnecessary randomness


NaCl has *deterministic* crypto_box and crypto_sign. Randomness only for keypair. Eliminates this type of disaster.

Also simplifies testing. NaCl uses automated test battery from eBACS (ECRYPT Benchmarking of Cryptographic Systems).
Avoiding pure crypto failures

Avoiding pure crypto failures


2012 Flame: new MD5 attack.
Avoiding pure crypto failures

2012 Flame: new MD5 attack.

Fact: By 1996, a few years after the introduction of MD5, Preneel and Dobbertin were calling for MD5 to be scrapped.

NaCl pays attention to cryptanalysis and makes very conservative choices of cryptographic primitives.
**Speed**

Crypto performance problems often lead users to reduce cryptographic security levels or give up on cryptography.

Example 1: Google SSL used RSA-1024 until 2013.

Security note: Analyses in 2003 concluded that RSA-1024 was breakable; e.g., 2003 Shamir–Tromer estimated 1 year, \( \approx 10^7 \) USD. RSA Labs and NIST response: Move to RSA-2048 by 2010.
Example 2: Tor used RSA-1024 until 2013 switch to Curve25519.

Example 3: DNSSEC uses RSA-1024: “tradeoff between the risk of key compromise and performance...”

Example 4: OpenSSL continues to use secret AES load addresses.

Example 5:
https://sourceforge.net/account is protected by SSL but
https://sourceforge.net/develop turns off crypto: redirects to
http://sourceforge.net/develop.
NaCl has no low-security options. e.g. `crypto_box` always encrypts *and* authenticates.

e.g. no RSA-1024; not even RSA-2048.
NaCl has no low-security options. e.g. `crypto_box` always encrypts and authenticates. e.g. no RSA-1024; not even RSA-2048.

Remaining risk: Users find NaCl too slow $\Rightarrow$ switch to low-security libraries or disable crypto entirely.
NaCl has no low-security options. e.g. crypto_box always encrypts and authenticates.
e.g. no RSA-1024; not even RSA-2048.

Remaining risk:
Users find NaCl too slow \(\Rightarrow\) switch to low-security libraries or disable crypto entirely.

How NaCl avoids this risk:
NaCl is exceptionally fast. Much faster than other libraries. 
*Keeps up with the network.*
NaCl operations per second for any common packet size, using AMD Phenom II X6 1100T CPU ($190 in 2011):

- crypto_box: >80000.
- crypto_box_open: >80000.
- crypto_sign_open: >70000.
- crypto_sign: >180000.
NaCl operations per second for any common packet size, using AMD Phenom II X6 1100T CPU ($190 in 2011):

- crypto_box: >80000.
- crypto_box_open: >80000.
- crypto_sign_open: >70000.
- crypto_sign: >180000.

Handles arbitrary packet floods up to ≈30 Mbps per CPU, depending on protocol details.
But wait, it’s even faster!

1. Pure secret-key crypto for any packet size:
   80000 1500-byte packets/second fill up a 1 Gbps link.

2. Pure secret-key crypto for many packets from same public key,
   if application splits 
   crypto_box into 
   crypto_box_beforenm and 
   crypto_box_afternm.
3. Very fast rejection of forged packets under known public keys: no time spent on decryption.

(This doesn’t help much for forgeries under new keys, but flooded server can continue providing fast service to known keys.)

4. Fast batch verification, doubling speed of crypto_sign_open for valid signatures.
Cryptographic details

The main NaCl work we did: achieve very high speeds without compromising security.

ECC, not RSA: much stronger security record.
Curve25519, not NSA/NIST curves: safecurves.cr.yp.to

Salsa20, not AES: much larger security margin.
Poly1305, not HMAC: information-theoretic security.
EdDSA, not ECDSA: collision-resilience et al.
Speed education

Oops, there’s another risk: users completely unaware of how fast crypto can be.
Speed education

Oops, there’s another risk: users completely unaware of how fast crypto can be.

Example:

“PRESERVE contributes to the security and privacy of future vehicle-to-vehicle and vehicle-to-infrastructure communication systems by addressing critical issues like performance, scalability, and deployability of V2X security systems.”

preserve-project.eu
“[In] most driving situations . . . the packet rates do not exceed 750 packets per second. Only the maximum highway scenario . . . goes well beyond this value (2,265 packets per second). . . .

Processing 1,000 packets per second and processing each in 1 ms can hardly be met by current hardware. As discussed in [32], a Pentium D 3.4 GHz processor needs about 5 times as long for a verification . . . a dedicated cryptographic co-processor is likely to be necessary.”
“NEON crypto” (CHES 2012) on 1GHz Cortex A8 core:
5.48 cycles/byte (1.4 Gbps),
2.30 cycles/byte (3.4 Gbps)
for Salsa20, Poly1305.
498349 cycles (2000/second),
624846 cycles (1600/second)
for Curve25519 DH, verify.
“NEON crypto” (CHES 2012) on 1GHz Cortex A8 core:
5.48 cycles/byte (1.4 Gbps),
2.30 cycles/byte (3.4 Gbps)
for Salsa20, Poly1305.
498349 cycles (2000/second),
624846 cycles (1600/second)
for Curve25519 DH, verify.

1GHz Cortex A8 was high-end smartphone core in 2010: e.g.,
Samsung Exynos 3110 (Galaxy S);
TI OMAP3630 (Motorola Droid X);
Apple A4 (iPad 1/iPhone 4).
“NEON crypto” (CHES 2012) on 1GHz Cortex A8 core: 5.48 cycles/byte (1.4 Gbps), 2.30 cycles/byte (3.4 Gbps) for Salsa20, Poly1305. 498349 cycles (2000/second), 624846 cycles (1600/second) for Curve25519 DH, verify.

1GHz Cortex A8 was high-end smartphone core in 2010: e.g., Samsung Exynos 3110 (Galaxy S); TI OMAP3630 (Motorola Droid X); Apple A4 (iPad 1/iPhone 4). 2013: Allwinner A13, $5 in bulk.
Case study: EdDSA

1985 ElGamal signatures:

\((R, S)\) is signature of \(M\)

if \(B^{H(M)} \equiv A^R R^S \pmod{q}\)

and \(R, S \in \{0, 1, \ldots, q - 2\}\).

Here \(q\) is standard prime, 
\(B\) is standard base,
\(A\) is signer’s public key, 
\(H(M)\) is hash of message.

Signer generates \(A\) and \(R\) as secret powers of \(B\); easily solves for \(S\).
1990 Schnorr improvements:

1. Hash $R$ in the exponent:
   \[ B^{H(M)} \equiv A^{H(R)} R^S. \]
   Reduces attacker control.

2. Replace three exponents with two exponents:
   \[ B^{H(M)/H(R)} \equiv A R^S/H(R). \]
   Saves time in verification.

3. Simplify by relabeling $S$:
   \[ B^{H(M)/H(R)} \equiv A R^S. \]
   Saves time in verification.

4. Merge the hashes:
   \[ B^{H(R,M)} \equiv A R^S. \]
   \[ \Rightarrow \text{Resilient to } H \text{ collisions.} \]
5. Eliminate inversions for signer: 
\[ B^S \equiv RA^{H(R,M)} \]
Simpler, faster.

6. Compress \( R \) to \( H(R, M) \).
Saves space in signatures.

7. Use half-size \( H \) output.
Saves space in signatures.
5. Eliminate inversions for signer: 
\[ B^S \equiv RA^{H(R, M)}. \]
Simpler, faster.

6. Compress \( R \) to \( H(R, M) \).
Saves space in signatures.

7. Use half-size \( H \) output.
Saves space in signatures.

Subsequent research: extensive theoretical study of security of Schnorr’s system.
5. Eliminate inversions for signer: \( B^S \equiv RA^{H(R, M)} \).
Simpler, faster.

6. Compress \( R \) to \( H(R, M) \).
Saves space in signatures.

7. Use half-size \( H \) output.
Saves space in signatures.

Subsequent research: extensive theoretical study of security of Schnorr’s system.

But patented. \( \Rightarrow \) DSA, ECDSA avoided most improvements.
5. Eliminate inversions for signer: \( B^S \equiv RA^{H(R,M)} \).
Simpler, faster.

6. Compress \( R \) to \( H(R, M) \).
Saves space in signatures.

7. Use half-size \( H \) output.
Saves space in signatures.

Subsequent research: extensive theoretical study of security of Schnorr’s system.

But patented. \( \Rightarrow \) DSA, ECDSA avoided most improvements.

Use elliptic curves in “complete –1-twisted Edwards” form.
⇒ very high speed,
natural side-channel protection,
no exceptional cases.
Skip signature compression.
Support batch verification.
Use double-size \( H \) output,
and include \( A \) as input.
Generate \( R \) deterministically
as a secret hash of \( M \).
⇒ Avoid PlayStation disaster.